Acquisition of Ice Thickness and Ice Surface Characteristics in the Seasonal Ice Zone by CULPIS-X during the US Coast Guard's Arctic Domain Awareness Program

Year 3 Report

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NAVAIR Applied Aerodynamics and Store Separation Branch Head: Frank Taverna

LONG-TERM GOALS

- Teaming with the SIZRS effort (J. Morrison, Univ. Washington; PI) to:
  - Investigate new technologies, e.g., sensors, platforms and communications, for sustained operation and observation in the challenging Arctic environment
  - Improve understanding of the physical environment and processes in the Arctic Ocean

OBJECTIVES

- *What is the volume of sea ice in the Beaufort Sea Seasonal Ice Zone (SIZ) and how does this evolve during summer as the ice edge retreats*? Recent observations suggest that the remaining ice in the Beaufort Sea is younger and thinner in recent years in part because even the oldest ice advected into the region does not survive the summer.
- *How does ice thickness relate to ice surface conditions, such as reflectance and ice surface temperature?* During summer, melting ice is covered extensively by melt ponds, which exhibit a reflectance considerably lower than the surrounding ice. Recent analyses have indicated that ponds on thinner ice are often darker, accelerating the ice-albedo feedback over thin ice in summer. During winter, leads and very thin ice are centers for ocean-atmosphere heat flux, so their fractional coverage and contribution to the surface-to-atmosphere heat flux need to be quantified.

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APPROACH

We plan to utilize the US Coast Guard's (USCG) Arctic Domain Awareness (ADA) Program to fly our CULPIS-X (CU Laser Profiler Instrument – extended) and CULPIS-X2 packages over the Beaufort, Chukchi and Bering Seas. ADA utilizes the C-130 Hercules to fly once every two weeks from late March to late November each year. The ADA C-130 flights originate in Kodiak, Alaska and overfly, among other areas, the Chukchi and Beaufort Seas, providing a unique opportunity to provide extensive, repeated observations of sea ice and the ocean in the SIZ.

CULPIS-X has been designed by a University of Colorado-Boulder student team, led by PI M. Tschudi, to fit into a USCG C-130 flare tube and operate in a near-autonomous mode. The package contains a laser altimeter/profiler, skin-temperature pyrometer, nadir-viewing spectrometer, snapshot and video cameras, pressure and temperature sensors, aircraft inertial measurement unit, a differential-capable GPS receiver, and payload computer. The CULPIS lidar and a few other components were previously deployed in the Arctic as a package called CULPIS [*Crocker et al.,* 2012]. The CULPIS-X instruments are designed to measure:

- distance to surface measured at 400 observations per second (CULPIS lidar)
- surface reflectance (hyperspectral radiometer)
- surface temperature (Everest infrared thermometer)
- digital snapshots and continuous video
- aircraft pitch, roll, yaw and rates of motion
- GPS position (basic position fix and carrier phase data)
- barometric pressure

The CULPIS-X package is undergoing a safety review process encompassing the following steps:

1. A CULPIS-X design was provided to the evaluation vendor, the US Navy's Naval Air Systems Command (NAVAIR).
2. NAVAIR used our CAD design model to integrate with a C-130 model and perform Computational Fluid Dynamics (CFD) simulations to evaluate the affect of air flow around CULPIS-X at nominal C-130 flight speeds. This evaluation is now complete.
3. The output of the CFD simulations were input into a Finite Element Design (FED) model, which was developed here at CU-Boulder.
4. The results from the FED analysis have been forwarded to CG Aviation Logistics Center (ALC), where they will be analyzed and a final recommendation to fly CULPIS-X on the C-130 will be made.
5. On Aug 18, 2014, our point of contact at CG Kodiak informed us that the safety review at CG ALC did not make their priority list for this year. We were asked for and provided additional science motivation to have the project on this year's list, but was told other CG priorities were ranked higher. This project will be on ALC's priority list for next year. We will lobby to have

it reviewed as early in the year as possible, so it can fly on ADA flights if approved in spring 2015.

WORK COMPLETED

CFD Analysis

The CULPIS-X package design underwent flight approval evaluation via a US Coast Guard (USCG) subcontractor, the US Navy's Naval Air System Command (NAVAIR) at Pax River, MD. The primary NAVAIR personnel to perform the analysis were Cholwon Paek and Ryan Czerwiec, and their results were reviewed by Shawn Woodson and approved by Frank Taverna, all NAVAIR personnel.

The analysis utilized the geometry for the CULPIS-X instrument package using our CAD design and incorporated it into an existing C-130H CAD geometry (Figure 1).

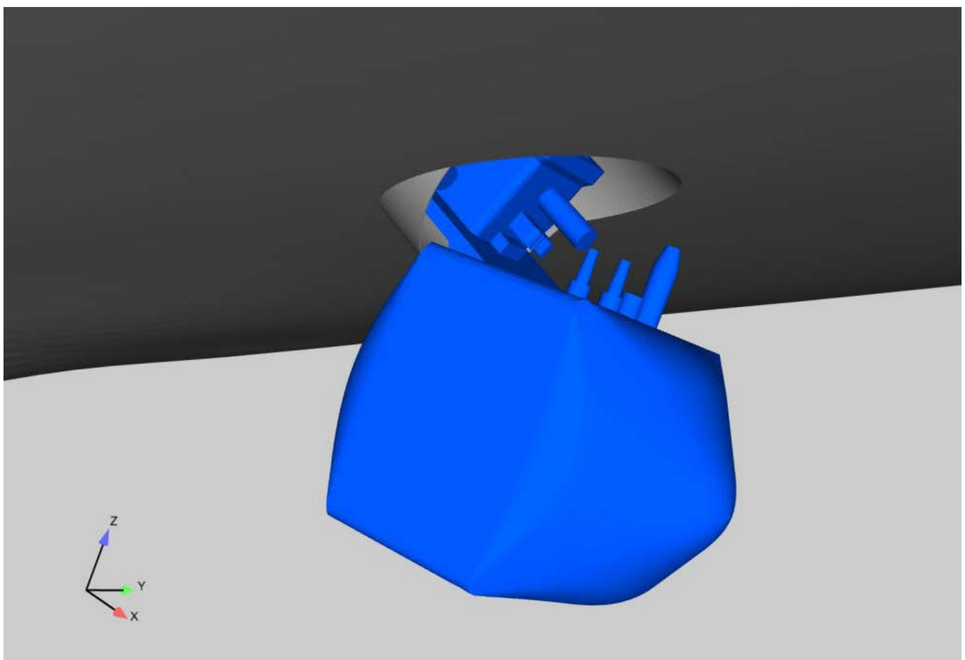

Figure 1: CULPIS-X probe (blue) on C-130.

NAVAIR then generated an unstructured surface and volume grid suitable for CFD analysis. The NAVAIR loads and dynamics group developed a list of flight conditions at the extremes of the aircraft flight envelope (Table 1). This determines the aircraft configuration (i.e. wing flap angles, operating engines, etc) and the number of CFD grids that need to be generated. A zero-degree flap setting for the cruise configuration was used for the test-point 1-6 cases, except for the test-point 7 case of which the trailing-edge flap setting was modeled for the takeoff condition, i.e., 18-degrees down. The time-accurate force and moment of CULPIS-X were computed with propellers, and the time-averaged data are computed and show in Table 2.

The NAVAIR group looked at flow characteristics, such as flow separation and reverse flow regions (e.g. Figure 2). The propeller effects were seen in the test-point cases where a significant sideslip angle was present. The driving frequencies of the force and moments were calculated to be about 10 Hz for all test-point cases. The driving frequencies are important to know along with the natural frequency of the CULPIS-X probe for its structural analysis within the flight envelope.

Table 1. CULPIS-X Flight Test Conditions selected by Loads group in NAVAIR.

Test point	Altitude ft	Speed KEAS	Mach	AoA deg.	Beta deg.	q_∞ psf	Flap deg.	Elevator deg.	Rudder deg.
1	0	172	0.2600	14.70	0	100	0	-19.9	0.0
2	0	202	0.3054	3.84	19.9	138	0	-0.6	-15.4
3	9950	320	0.5828	-2.26	0	347	0	8.7	0.0
4	200	197	0.2989	13.37	0	131	0	-13.0	0.0
5	100	320	0.4847	1.71	0	347	0	1.9	0.0
6	0	270	0.4082	0.85	10.36	247	0	0.8	-7.0
7	500	125	0.1907	14.70	19.9	53	18	-19.9	35.0

Table 2. Computational F&M predictions on the CULPIS-X probe in the body-axis system, based on the probe reference information.

Test point	Altitude ft	Speed keas	Mach	AoA deg	Beta deg	q_∞ psf	Fx lb	Fy lb	Fz lb	Mx in-lb	My in-lb	Mz in-lb
1	0	172	0.2600	14.70	0	100	58	1	7	-1	-978	-13
2	0	202	0.3054	3.84	19.9	138	57	-59	-18	1054	-316	1577
3	9950	320	0.5828	-2.26	0	347	126	3	41	-40	-2784	-71
4	200	197	0.2989	13.37	0	131	68	1	10	-1	-1194	-13
5	100	320	0.4847	1.71	0	347	129	-4	36	86	-2703	113
6	0	270	0.4082	0.85	10.36	247	107	-34	12	606	-1779	901
7	500	125	0.1907	14.70	19.9	53	67	-49	-5	586	-543	482

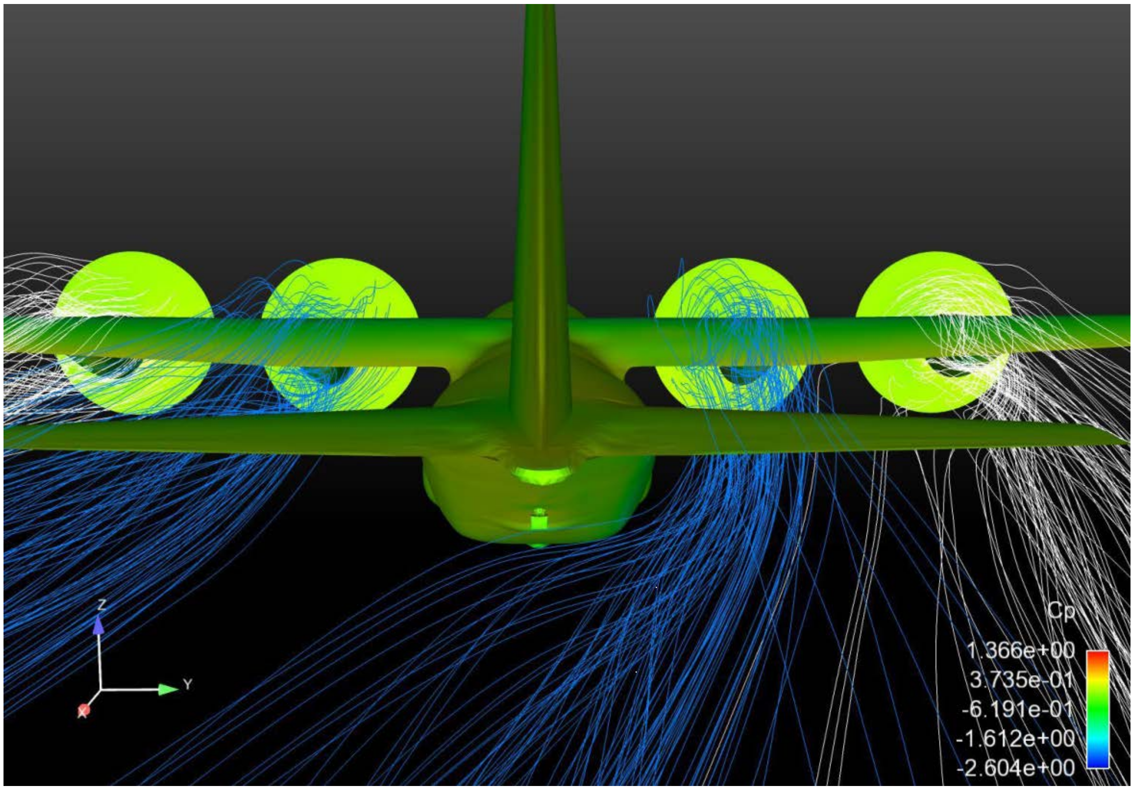

Figure 2: Propeller effects on CULPIS-X (green square in center) during cruising speed.

After NAVAIR completed the CFD analysis for CULPIS-X on the C-130, the results were relayed to CU-Boulder. The output of this CFD analyis, namely the forces and moments, were used as input to a Finite Element Design (FED) model designed for CULPIS-X by Pete Coffin, a doctoral student in the Department of Mechanical Engineering.

FED Analysis (P. Coffin)

This work is a follow-on to a previous structural analysis of steady inertial loads on the C-130 structure due to the CULPIS-X instrument package. The package mounts inside one of the C-130's are dispenser tubes that are located on the rear door. Previous structural analysis was completed using gravity-like loads resulting from steady accelerations in a variety of directions. Studying a 4g acceleration at a set of 231 directions, the maximum Von Mises was found to be 18% of the material yield stress.

The current work continues using the same Finite Element model but with more complicated loading. The loading applied resulted from time-varying aerodynamic loads provided by the Naval Air Systems Command (NAVAIR). As in the previous work, the effect of the instrument on the aircraft structure is of primary interest, so the Finite Element model includes the entire dispenser tube and only the main structural plate of the instrument package. Aerodynamic loads resulting from the exposed instrument are applied to the main plate as simplified forces and moments at the two points of attachment.
A six degree-of-freedom triangular shell element was chosen to model the flare tube, bracket and skin. Both the bracket and internal rails have stress concentrating characteristics that led to seeding those areas with half the element size used for the rest of the assembly. The material properties, including

thickness of the connections, are consistent with those of the main tube. The mesh size (Fig. 3) well-estimated the structures total deformation (strain energy).

Table 3 shows the maximum values of VonMises stress over the entire simulation time. Considering the yield strength of the weakest material (276 MPa), the maximum value of stress as a percentage of yield is 2.77%, providing a substantial margin. Cases 3, 5 and 6 all show to have the largest overall stresses and correspond to the congurations with the largest airspeed. Plotting the stress over the model (Figure 4) shows that the highest stress concentrations are at the tube-skin interface near the most substantial tube structure.

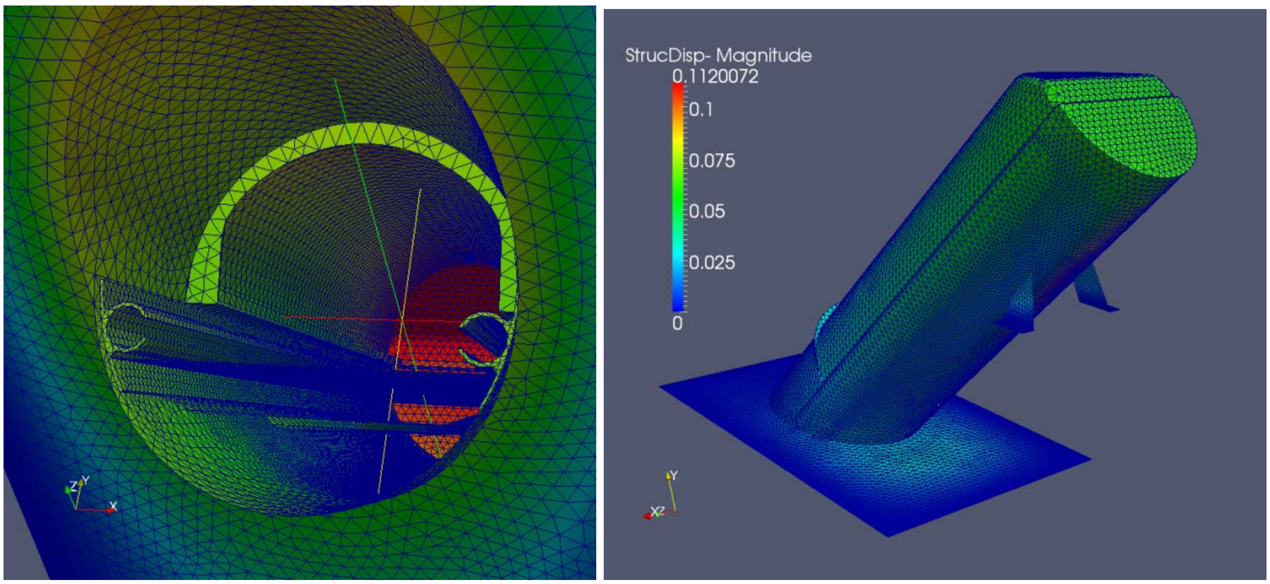

Figure 3: Mesh size used for analysis, scale factor = 0.4 inch, showing structural displacement magnitude and element edges.

Table 3: Maximum VonMises Stresses for the 7 test cases.

Test Case	Max VonMises Stress Over Run (MPa)	Percent of Yield
1	2.439	0.884
2	3.7463	1.36
3	7.066	2.56
4	2.981	1.08
5	7.640	2.77
6	6.006	2.18
7	3.904	1.41

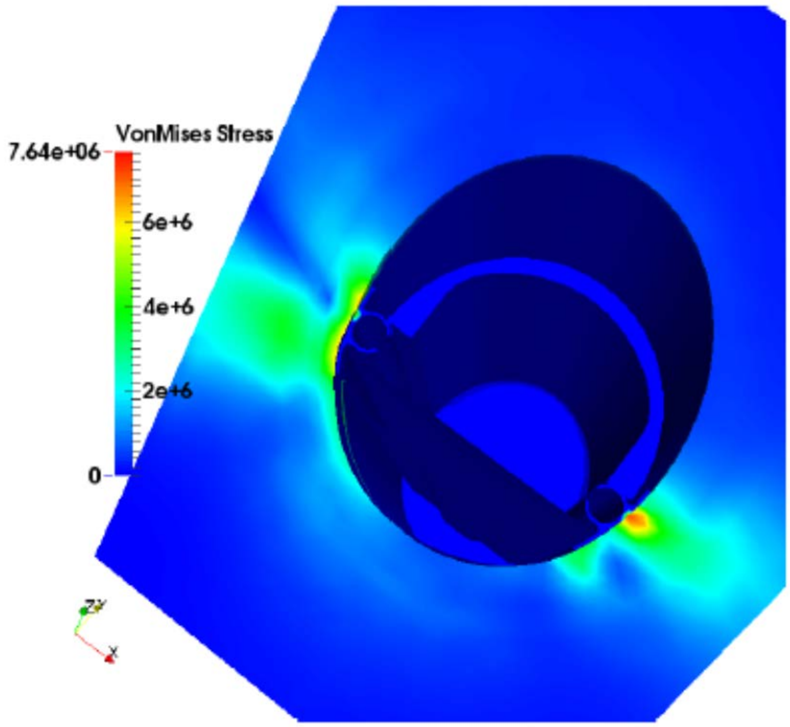

Figure 4: VonMises stress plotted over the FED model.

The FED analysis thus found that the maximum stresses were substantially below yield, suggesting that CULPIS-X would fly safely in the flare tube under normal C-130 flight conditions. The final assessment of safety will be determined by the USCG ALC C-130 Engineer, LCDR Ben Schluckebier.

Software upgrades (J. Stark)

With spare time for the CULPIS-X package as the safety review process proceeded, an upgrade to the CULPIS-X data logging system and component integration was undertaken. This was deemed necessary due to some unfinished electronics work by the previous build team. A doctoral student at CU-Boulder, John Stark, was hired to perform these tasks under the supervision of M. Tschudi. He completed his work in August 2014. The summary of his work on the system follows:

An initial survey of the system identified three major subsystems that could be improved: software, power distribution, and the video & still camera control system. The bulk of the development effort was focused on moving the software towards flight readiness. The survey prompted a redesign of the software architecture. The legacy CULPIS software was heavily interrupt driven but this architecture was found to be undesirable when interfacing to the new sensors as well as being difficult to debug. The new architecture now uses a GPS time steered pulse per second, PPS, signal to drive the events occurring on each microcontroller. The advantages of this methodology include better compatibility with the new sensor package and improved field reliability.

Device drivers were re-written for the GPS board, the Ocean Optics spectrometer, Everest IR temperature, ULS Lidar, and the data logging system to support the new architecture. Testing was completed successfully and the new drivers' performance verified. A 24-hour test for interfacing to the GPS/GLONASS board was performed, to interface this system to the main C&DH board with a new driver written. Testing of this software was completed.

Once the software driver has been written and tested work will continue on implementing the new timing software architecture. This will begin by first interfacing in software the microcontrollers for the new sensors and the microcontroller controlling the new GPS board. Once this has been finished the drivers for the legacy sensors will be updated and their operation integrated into the overall architecture. Finally, the power distribution and still & video camera control system will be completed. Completion of these tasks is anticipated to be done by no later than the end of this calendar year.

The CULPIS-X instrument package has also been undergoing some hardware upgrades while we wait for the approval process to complete. New CU-Boulder team members KatieRae Williamson (graduate, Aero. Engineering) and William Tandy (doctoral student, Aero. Engineering and Ball Aerospace) have been hired to perform minor updates to the package while we wait for approval. The CULPIS-X package is lightweight (11.7 kg) with an aerodynamic structure (Figure 5). All instruments are fitted into the package, and the instrument box contains the newly-programmed electronics (Figure 6).

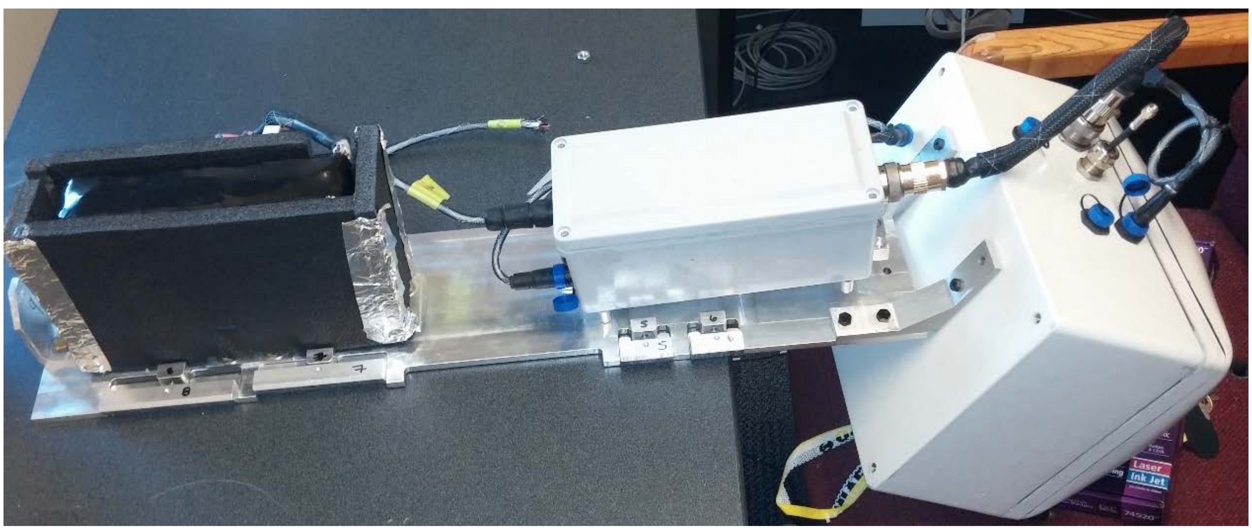

Figure 5: CULPIS-X instrument package. Sensor package on right, data acquisition box in middle, battery on left. Sleigh will fit in C-130 flare tube, box will protrude out flare tube.

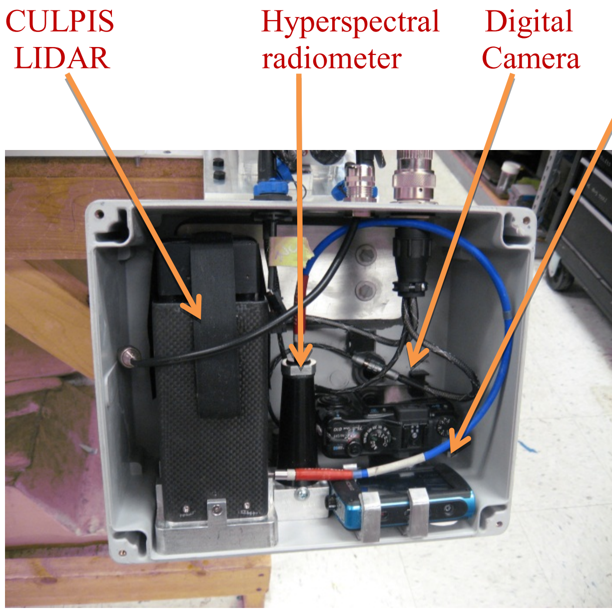

Figure 6a: CULPIS-X sensor package

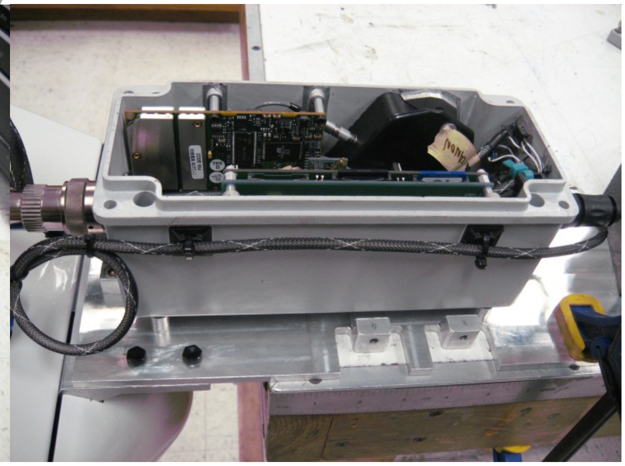

Figure 6b: CULPIS-X data acquisition box

RESULTS

We will move forward with finishing package upgrades by K. Williamson and W. Tandy, readying CULPIS-X for a “soft” test in Kodiak, AK. For the test, the package will be fitted into the C-130 flare tube, and turned on to test for any electromagnetic interference. We plan to perform this soft test in advance of the CG ALC review, during winter 2014-15, to provide the best opportunity for flight approval. Installation and operating instructions for CULPIS-X have been written and delivered to CG Kodiak. They will submit a new Aircraft Configuration Control Board (ACCB) request to CG ALC in Elizabeth City, NJ. Note that the original ACCB request was submitted in 2010.

We have been informed by CG ALC that CULPIS-X will not be reviewed for flight approval this year, but will be on the list for next year. We will lobby to have this review perfomed as early as possible next year, to ensure there are opportunities to deploy the package on multiple flights if it is approved.

IMPACT/APPLICATIONS

Note that several events have delayed the project from being submitted for CG approval. This project was delayed for several months in Year 2 due to the inability to transfer funds from CU-Boulder to the NAVAIR group. Eventually this transfer was performed by Martin Jeffries directly from ONR to NAVAIR and the work was performed in a timely manner.

Another delay was related to having to perform the FED analysis. This was originally a task that the CG ALC was to undertake, but their workloads and priorities resulted in the task being taken on by CU-Boulder.

We appreciate the continued support of ONR on this project, and are doing everything possible to have our package approved and deployed in 2015.

RELATED PROJECTS

SIZRS (J. Morrison, Univ. Washington; PI)

REFERENCES

Crocker, R. Ian, James A. Maslanik, John J. Adler, Scott E. Palo, Ute C. Herzfeld, and William J. Emery, 2012: A Sensor Package for Ice Surface Observations Using Small Unmanned Aircraft Systems. *IEEE Trans. Geoscience and Rem. Sens*., Vol. 50, No. 4, APRIL 2012.